Introduction
THE NATURAL WORLD

To every man the natural world seems immense and complex, the stage for a startling diversity of appearances and events. These impressions are supported by estimates of the general order of magnitude of the values of interesting quantities concerning the natural world. At this stage we shall not enter into the arguments and measurements that lead to the figures given. The most remarkable thing about these numbers is that we know them at all; it is not of pressing importance that some of them are known only approximately.

The universe is immense. From astronomical observations we infer the value $10^{28}$ centimeters (cm) or $10^{10}$ light years (yr) for a characteristic dimension loosely called the radius of the universe. The value is uncertain by perhaps a factor of 3. For comparison, the distance of the earth from the sun is $1.5 \times 10^{13}$ cm and the radius of the earth is $6.4 \times 10^8$ cm.

The number of atoms in the universe is very large. The total number of protons and neutrons in the universe, with an uncertainty perhaps of a factor of 100, is believed to be of the order of $10^{80}$. Those in the sun number $1 \times 10^{57}$, and those in the earth $4 \times 10^{51}$. The total in the universe would provide about $10^{50}/10^{51}$ (or $10^{50}$) stars equal in mass to our sun. [For comparison, the number of atoms in an atomic weight (Avogadro's number) is $6 \times 10^{23}$.] Most of the mass of the universe is believed to lie in stars, and all known stars have masses between 0.01 and 100 times that of our sun.

Life appears to be the most complex phenomenon in the universe. Man, one of the more complex forms of life, is composed of about $10^{16}$ cells. A cell is an elementary physiological unit that contains about $10^{12}$ to $10^{14}$ atoms. Every cell of every variety of living matter is believed to contain at least one long molecular strand of DNA (deoxyribonucleic acid) or of its close relative RNA (ribonucleic acid). The DNA strands in a cell hold all the chemical instructions, or genetic information, needed to construct a complete man, bird, etc. In a DNA molecule, which may be composed of $10^8$ to $10^{10}$ atoms, the precise arrangement of the atoms may vary from individual to individual; the arrangement always varies from species to species.\(^1\) More than $10^9$ species have been described and named on our planet.

Inanimate matter also appears in many forms. Protons, neutrons, and electrons combine to form about one-hundred

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\(^1\)The term species is defined roughly by the statement that two populations are different species if some describable difference(s) can be found between them and if they do not interbreed in a state of nature
different chemical elements and about $10^3$ identified isotopes. The individual elements have been combined in various proportions to form perhaps $10^6$ or more identified, differentiated chemical compounds, and to this number may be added a vast number of liquid and solid solutions and alloys of various compositions having distinctive physical properties.

Through experimental science we have been able to learn all these facts about the natural world, to classify the stars and to estimate their masses, compositions, distances, and velocities; to classify living species and to unravel their genetic relations; to synthesize inorganic crystals, biochemicals, and new chemical elements; to measure the spectral emission lines of atoms and molecules over a frequency range from 100 to $10^{20}$ cycles per second (cps); and to create new fundamental particles in the laboratory.

These great accomplishments of experimental science were achieved by men of many types: patient, persistent, intuitive, inventive, energetic, lazy, lucky, narrow, and with skilled hands. Some preferred to use only simple apparatus; others invented or built instruments of great refinement, size, or complexity. Most of these men had in common only a few things: They were honest and actually made the observations they recorded, and they published the results of their work in a form permitting others to duplicate the experiment or observation.

THE ROLE OF THEORY

The description we have given of the natural universe as immense and complex is not the whole story, for theoretical understanding makes several parts of the world picture look much simpler. We have gained a remarkable understanding of some central and important aspects of the universe. The areas that we believe we understand (summarized below), together with the theories of relativity and of statistical mechanics, are among the great intellectual achievements of mankind.

1 The laws of classical mechanics and gravitation (Volume I), which allow us to predict with remarkable accuracy the motions of the several parts of the solar system (including comets and asteroids), have led to the prediction and discovery of new planets. These laws suggest possible mechanisms for the formation of stars and galaxies, and, together

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1 The approved unit for cycles per second has become Hertz (Hz), and so this phrase could have been written “from 100 to $10^{20}$ Hz.”
with the laws of radiation, they give a good account of the observed connection between the mass and luminosity of stars. The astronomical applications of the laws of classical mechanics are the most beautiful but not the only successful applications. We use the laws constantly in everyday life and in the engineering sciences. Our contemporary ventures into space and the use of satellites are based upon refined applications of the laws of classical mechanics and gravitation.

2. The laws of quantum mechanics (Volume 4) give a very good account of atomic phenomena. For simple atoms predictions have been made that agree with experiment to 1 part in $10^8$ or better. When applied to large-scale terrestrial and celestial events, the laws of quantum mechanics result in predictions indistinguishable from the laws of classical mechanics. Quantum mechanics provides, in principle, a precise theoretical basis for all of chemistry and metallurgy and for much of physics, but often we cannot handle the equations on existing or foreseeable computers. In some fields nearly all the problems seem too difficult for a direct theoretical attack based on first principles.

3. The laws of classical electrodynamics, which give an excellent account of all electric and magnetic effects, except on the atomic scale, are the basis of the electrical engineering and communications industries. Electric and magnetic effects on the atomic scale are described exactly by the theory of quantum electrodynamics. Classical electrodynamics is the subject of Volumes 2 and 3; some aspects of quantum electrodynamics are touched on in Volume 4, but a complete discussion of the field must be deferred until a later course.

4. At another, narrower level, the principle of operation of the genetic code is understood—in particular, the mechanism of storage of genetic information. We find that the information storage of the cell of a simple organism exceeds that of the best present-day commercial computers. In nearly all life on our planet the complete coding of genetic information is carried in the DNA molecule by a double linear sequence (possessing $10^6$ to $10^9$ entries, depending on the organism) of only four different molecular groups, with specific but simple rules governing the pairing of members opposite each other in the double sequence (see Fig. 1.1). These matters are a part of the subject of molecular biology.
The physical laws and theoretical understanding mentioned in the above summaries are different in character from the direct results of experimental observations. The laws, which summarize the essential parts of a large number of observations, allow us to make successfully certain types of predictions, limited in practice by the complexity of the system. Often the laws suggest new and unusual types of experiments. Although the laws can usually be stated in compact form, their application may sometimes require lengthy mathematical analysis and computation.

There is another aspect of the fundamental laws of physics: Those laws of physics that we have come to understand have an attractive simplicity and beauty. This does not mean that everyone should stop doing experiments, for the laws of physics have generally been discovered only after painstaking and ingenious experiments. The statement does mean that we shall be greatly surprised if future statements of physical theory contain ugly and clumsy elements. The aesthetic quality of the discovered laws of physics colors our expectations about the laws still unknown. We tend to call a hypothesis attractive when its simplicity and elegance single it out among the large number of conceivable theories.

In this course we shall make an effort to state some of the laws of physics from viewpoints that emphasize the features of simplicity and elegance. This requires that we make considerable use of mathematical formulations, although at the present level of study this use normally will not exceed the bounds of introductory calculus. As we go along, we shall try also to give some of the flavor of good experimental physics, although this is very hard to do in a textbook. The research laboratory is the natural training ground in experimental physics.

GEOMETRY AND PHYSICS

Mathematics, which permits the attractive simplicity and compactness of expression necessary for a reasonable discussion of

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2. "It seems that if one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress" P. A. M. Dirac, Scientific American, 208 (5) 45–53 (1963). But most physicists feel the real world is too subtle for such bold attacks except by the greatest minds of the time, such as Einstein or Dirac or a dozen others. In the hands of a thousand others this approach has been limited by the inadequate distribution among men of "a sound insight."
the laws of physics and their consequences, is the language of physics. It is a language with special rules. If the rules are obeyed, only correct statements can be made: The square root of 2 is 1.414 . . . , or \( \sin 2a = 2 \sin a \cos a \).

We must be careful not to confuse such truths with exact statements about the physical world. It is a question of experiment, rather than contemplation, to see whether the measured ratio of the circumference to the diameter of a physical circle really is 3.14159 . . . . Geometrical measurement is basic to physics, and we must decide such questions before proceeding to use euclidean or any other geometry in the description of nature. Here certainly is a question about the universe: Can we assume for physical measurements the truth of the axioms and theorems of Euclid?

We can say only a few simple things about the experimental properties of space without becoming involved in difficult mathematics. The most famous theorem in all mathematics is that attributed to Pythagoras: For a right-angled triangle the square of the hypotenuse equals the sum of the squares of the adjacent sides (Fig. 1.2). Does this mathematical truth, which assumes the validity of euclidean geometry, also hold true in the physical world? Could it be otherwise? Contemplation of the question is insufficient, and we must appeal to experiment for an answer. We give arguments that are somewhat incomplete because here we are not able to use the mathematics of curved three-dimensional space.

Consider first the situation of two-dimensional beings who live in a universe that is the surface of a sphere. Their mathematicians have described to them the properties of spaces of three dimensions or even more, but they have as much difficulty in developing an intuitive feeling about such matters as we have in picturing four-dimensional space. How can they determine whether they live on a curved surface? One way is to test the axioms of plane geometry by trying to confirm experimentally some of the theorems in Euclid. They may construct a straight line as the shortest path between any two points \( B \) and \( C \) on the surface of a sphere; we would describe such a path as a great circle, as shown in Fig. 1.3. They can go on to construct triangles and to test the pythagorean theorem. For a very small triangle, each of whose sides is small in comparison with the radius of the sphere, the theorem would hold with great but not perfect accuracy; for a large triangle striking deviations would become apparent (see Figs. 1.4 to 1.6).

If \( B \) and \( C \) are points on the equator of the sphere, the “straight line” connecting them is the section of the equator
from $B$ to $C$. The shortest path from $C$ on the equator to the north pole $A$ is the line of fixed longitude that meets the equator $BC$ at a right angle. The shortest path from $A$ to $B$ is a path of fixed longitude that also meets the equator $BC$ at a right angle. Here we have a right triangle with $b = c$. The pythagorean theorem is clearly invalid on the sphere because $c^2$ cannot now be equal to $b^2 + a^2$; further, the sum of the interior angles of the triangle $ABC$ is always greater than $180^\circ$. Measurements made on the curved surface by its two-dimensional inhabitants enable them to demonstrate for themselves that the surface is indeed curved.

It is always possible for the inhabitants to say that the laws of plane geometry adequately describe their world, but the trouble lies with the meter sticks used to measure the shortest path and thus define the straight line. The inhabitants could say that the meter sticks are not constant in length but stretch and shrink as they are moved to different places on the surface. Only when it is determined by continued measurements in different ways that the same results always hold does it become evident that the simplest description of why euclidean geometry fails lies in the curvature of the surface.

The axioms of plane geometry are not self-evident truths in this curved two-dimensional world; they are not truths at all. We see that the actual geometry of the universe is a branch of physics that must be explored by experiment. We do not customarily question the validity of euclidean geometry to describe measurements made in our own three-dimensional world because euclidean geometry is such a good approximation to the geometry of the universe that any deviations from it do not show up in practical measurements. This does not mean that the applicability of euclidean geometry is self-evident or even exact. It was suggested by the great nineteenth-century mathematician Carl Friedrich Gauss that the euclidean flatness of three-dimensional space should be tested by measuring the sum of the interior angles of a large triangle; he realized that if three-dimensional space is curved, the sum of the angles of a large enough triangle might be significantly different from $180^\circ$.

Gauss\(^1\) used surveying equipment (1821–1823) to measure accurately the triangle in Germany formed by Brocken, Hohehagen, and Inselberg (Fig. 1.7). The longest side of the triangle

\(^1\) C. F. Gauss, "Werke," vol. 9, B. G. Teubner, Leipzig, 1903. see especially pp. 299, 300, 314, and 319. The collected works of Gauss are a remarkable example of how much a gifted man can accomplish in a lifetime.
FIG. 1.6 For this triangle, with $B$ and $C$ below the equator, $\alpha + \beta > 180^\circ$, which can only happen because the two-dimensional "space" of the spherical surface is curved. A similar argument can be applied to three-dimensional space. The radius of curvature of the two-dimensional space shown here is just the radius of the sphere.

![Diagram of a triangle on a spherical surface]

FIG. 1.7 Gauss measured the angles of a triangle with vertices on three mountain tops and found no deviation from $180^\circ$ within the accuracy of his measurements.

was about 100 kilometers (km). The measured interior angles were:

- $86^\circ 13' 58.366''$
- $53^\circ 6' 45.642''$
- $40^\circ 39' 30.165''$

Sum $180^\circ 00' 14.173''$

(We have not found a statement about the estimated accuracy of these values; it is likely that the last two decimal places are not significant.) Because the surveying instruments were set up locally horizontal at all three vertices, the three horizontal planes were not parallel. A calculated correction called the spherical excess, which amounts to $14.853''$ of arc, must be subtracted from the sum of the angles. The sum thus corrected, $179^\circ 59' 59.320''$, differs by $0.680''$ of arc from $180^\circ$. Gauss believed this to lie within the observational error, and he concluded that space was euclidean within the accuracy of these observations.

We saw in the earlier example that euclidean geometry adequately described a small triangle on the two-dimensional sphere but departures became more evident as the scale increased. To see if our own space is indeed flat we need to measure very large triangles whose vertices are formed by the earth and distant stars or even galaxies. But we are faced with a problem: Our position is fixed by that of the earth and we are not yet free to wander through space with instruments to measure astronomical triangles. How can we test the validity of euclidean geometry to describe measurements in space?

Estimates of the Curvature of Space

**Planetary Predictions** A first lower limit of about $5 \times 10^{17}$ cm to the radius of curvature of our own universe is implied by the consistency of astronomical observations within the solar system. For example, the positions of the planets Neptune and Pluto were inferred by calculation before their visual confirmation by telescopic observation. Small perturbations of the orbits of the known planets led to this discovery of Neptune and Pluto very close to the positions calculated for them. The outermost planet in the solar system is Pluto, and we can easily believe that a slight error in the laws of geometry would have destroyed this coincidence. The average radius of the orbit of Pluto is $6 \times 10^{14}$ cm; the closeness of the coincidence between the predicted and observed positions implies a radius of curvature...
of space of at least $5 \times 10^{17}$ cm. An infinite radius of curvature (flat space) is not incompatible with the data. It would take us too far from our present purpose to discuss the numerical details of how the estimate of $5 \times 10^{17}$ cm is arrived at or to define precisely what is meant by the radius of curvature of a three-dimensional space. The two-dimensional analog of the surface of a sphere can be used in this emergency as a useful crutch.

**Trigonometrical Parallax** Another argument was suggested by Schwarzschild.\(^1\) In two observations taken 6 months apart, the position of the earth relative to the sun has changed by $3 \times 10^{13}$ cm, the diameter of the earth’s orbit. Suppose that at these two times we observe a star and measure the angles $\alpha$ and $\beta$ as in Fig. 1.8. (Here $\alpha$ and $\beta$ are the Greek characters alpha and beta.) If space is flat, the sum of the angles $\alpha + \beta$ is always less than $180^\circ$ and the sum approaches this value as the star becomes infinitely distant. One-half of the deviation of $\alpha + \beta$ from $180^\circ$ is called the parallax. But in a curved space it is not necessarily true that $\alpha + \beta$ is always less than $180^\circ$. An example is shown in Fig. 1.6.

We return to our hypothetical situation of two-dimensional astronomers living on the surface of a sphere to see how they discover that their space is curved from a measurement of the sum $\alpha + \beta$. From our previous discussion of the triangle $ABC$ we see that when the star is a quarter of a circumference away, $\alpha + \beta = 180^\circ$; when the star is nearer, $\alpha + \beta < 180^\circ$; and when it is farther away, $\alpha + \beta > 180^\circ$. The astronomer need merely look at stars more and more distant and measure $\alpha + \beta$ to see when the sum begins to exceed $180^\circ$. The same argument is valid within our three-dimensional space.

There is no observational evidence that $\alpha + \beta$ as measured by astronomers is ever greater than $180^\circ$, after an appropriate correction is made for the motion of the sun relative to the center of our galaxy. Values of $\alpha + \beta$ less than $180^\circ$ are used to determine by triangulation the distances of nearby stars. Values less than $180^\circ$ can be observed out to about $3 \times 10^{20}$ cm,\(^\dagger\) the limit of angle measurement with present telescopes. It cannot be inferred directly from this argument

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\(^1\) Schwarzschild, *Vierteljahrsschrift der astronomen Ges.* 36:337 (1900)

\(^\dagger\) It may be objected that the distance measurements themselves assume that euclidean geometry is applicable. Other methods of estimating distance are available, however, and are discussed in modern texts on astronomy.
that the radius of curvature of space must be larger than 3 × 10^{20} \text{ cm}; for some types of curved space other arguments are needed. The answers come out finally that the radius curvature (as determined by triangulation) must be larger than 6 × 10^{19} \text{ cm}.

At the beginning of this chapter we said that a characteristic dimension associated with the universe is inferred to have a value of the order of 10^{28} \text{ cm} or 10^{10} \text{ light yr}. This number corresponds, for example, to the distance light would travel in a time equal to the age of the universe as inferred from observations that would be too lengthy to present here. The most elementary interpretation of this length calls it the radius of the universe; another possible interpretation calls the radius of curvature of space. Which is it? This is a cosmological question. (An excellent introduction to the speculative science of cosmology is given in the book by Bondi cited in the Further Reading section at the end of this chapter.) We summarize our belief about the radius of curvature of space by the statements that it is not smaller than 10^{28} \text{ cm} and that we do not know that space on a large scale is not flat.

The foregoing observations bear upon the average radii of curvature of space and are not sensitive to bumps that are believed to exist in the immediate neighborhood of individual stars and that contribute a local roughness to the otherwise flat, or slightly curved, space. Experimental data that bear upon this question are extremely hard to acquire, even for the neighborhood of our sun. By careful and difficult observations of stars visible near the edge of the sun during a solar eclipse, it has been established that light rays are slightly curved when the path near the edge of the sun and, by inference, close to or similarly massive star (see Figs. 1.9 and 1.10). For a grazing ray the angle of bend is very slight, amounting to only 1.75. Thus as the sun moves through the sky the stars that are almost eclipsed, if we could see them in the daytime, would appear to spread out very slightly from their normal positions. This observation merely says that the light moves in a curved path near the sun; it does not by itself insist upon the unique interpretation that the space around the sun is curved. Only with accurate measurements by various measuring instruments close to the sun’s surface could we establish directly that a curve space is the most efficient and natural description. One other kind of observation bears upon the possibility of a curved space. The orbit of Mercury, the planet nearest the sun, differs very

\footnote{One evidence for this is mentioned in Chap. 10 (page 319).}
slightly from that predicted by application of Newton's laws of universal gravitation and motion (see Fig. 14.9). Could this be an effect of curved space near the sun? To answer such a question we would have to know how a possible curvature would affect the equations of motion for Mercury, and this involves more than just geometry. [These topics are discussed further (but briefly) in Chap. 14.]

In a remarkable and beautiful series of papers, Einstein [A. Einstein, *Berl. Ber.*, 778, 799, 844 (1915); *Ann. d. Phys.* *49*: 769 (1916)] described a theory of gravitation and geometry, the general theory of relativity, which predicted, in quantitative agreement with the observations, just the two effects described above. There are still few confirmations of the geometric predictions of the theory. However, despite the meager evidence, the essential simplicity of the general theory has made it widely accepted, although in recent years there has been considerable research in this field (see Chap. 14).

**Geometry on a Smaller Scale**

From astronomical measurements we concluded that euclidean geometry gives an extraordinarily good description of measurements of lengths, areas, and angles, at least until we reach the enormous lengths of the order of $10^{28}$ cm. But so far nothing has been said about the use of euclidean geometry to describe very small configurations comparable in size to the $10^{-8}$ cm of an atom or the $10^{-12}$ cm of a nucleus. The question of the validity of euclidean geometry ultimately must be phrased as follows: Can we make sense of the subatomic world, can we make a successful physical theory to describe it, while assuming that euclidean geometry is valid? If we can, then there is no reason at present to question euclidean geometry as a successful approximation. We shall see in Volume 4 that the theory of atomic and subatomic phenomena does not seem to lead to any paradoxes that have thus far blocked our understanding of them. Many facts are not understood, but none appear to lead to contradictions. In this sense euclidean geometry stands the test of experiment down at least to $10^{-13}$ cm.

**INVARINANCE**

We shall summarize some of the consequences of the experimental validity of euclidean geometry for empty space. The *homogeneity* and *isotropy* of euclidean space can be expressed by two invariance principles, which, in turn, imply two fundamental conservation principles.
Invariance under Translation  
By this principle we mean that empty space is homogeneous, i.e., that it is not different from point to point. If figures are moved without rotation from one location to another, there is no change in their size or geometric properties. We assume also that the physical properties of an object, such as its inertia or the forces between its constituent particles, do not change merely upon displacing the object to another region of empty space. Thus the natural frequency of a tuning fork or the characteristic spectrum lines of an atom are not altered by such displacement.

Invariance under Rotation  
By experiment it is known that empty space is isotropic to high precision, so that all directions are equivalent. Geometric and physical properties are unaltered by the reorientation in direction of an object in empty space. It is possible to imagine a space that is not isotropic; for example, the speed of light in some direction could be greater than its value in another direction at right angles to the first. There is no evidence in free space for an effect of this kind; within a crystal, however, many such anisotropic effects are encountered. In regions of space close to massive stars and other strong sources of gravitation, effects can be observed that may be interpreted as slight departures from homogeneity and isotropy of space. (We have alluded to two such effects in the preceding section, and there are others.)

The property of invariance under translation leads to the conservation of linear momentum; invariance under rotation leads to the conservation of angular momentum. These conservation principles are developed in Chaps. 4 and 6, and the concept of invariance is developed in Chaps. 2 and 4.

The foregoing lengthy discussion about geometry and physics is an example of the types of questions that physicists must ask about the basic character of our universe. But we shall not treat such matters further at this level of our study.

### PROBLEMS

1. The known universe. Using information in the text, estimate the following:
   
   \( a \)  The total mass in the known universe.  
   \( \text{Ans.} \approx 10^{50} \text{ g.} \)

   \( b \)  The average density of matter in the universe.  
   \( \text{Ans.} \approx 10^{-20} \text{ g/cm}^3, \text{ equivalent to } 10 \text{ hydrogen atoms/m}^3. \)

   \( c \)  The ratio of the radius of the known universe to that of a proton. Take the radius of the proton to be \( 1 \times 10^{-15} \text{ cm} \) and the mass of the proton to be \( 1.7 \times 10^{-24} \text{ g} \).

2. Signals across a proton. Estimate the time required for a signal traveling with the speed of light to move a distance equal to the diameter of a proton. Take the diameter of the
proton to be $2 \times 10^{-13}$ cm. (This time is a convenient reference interval in the physics of elementary particles and nuclei.)

3. *Distance of Sirius.* The parallax of a star is one-half the angle subtended at the star by the extreme points in the earth's orbit around the sun. The parallax of Sirius is 0.371". Find its distance in centimeters, light years, and parsecs. One parsec is the distance to a star whose parallax is 1". (See the table of values inside the front and back covers.)

Ans. $8.3 \times 10^{18}$ cm; 8.8 light yr; 2.7 parsecs.

4. *Size of atoms.* Using the value of Avogadro's number given in the table inside the back cover of the book and your estimate of an average density for common solids, estimate roughly the diameter of an average atom, that is, the dimension of the cubical space filled by the atom.

5. *Angle subtended by moon.* Obtain a millimeter scale and, when viewing conditions are favorable, try the following experiment: Hold the scale at arm's length and measure the diameter of the moon; measure the distance from the scale to your eye. (The radius of the moon's orbit is $3.8 \times 10^{10}$ cm, and the radius of the moon itself is $1.7 \times 10^8$ cm.)

(a) If you were able to try the measurement, what was the result?

(b) If the measurement could not be made, from the data given above calculate the angle subtended by the moon at the earth.

Ans. $9 \times 10^{-3}$ radians (rad).

(c) What is the angle subtended at the moon by the earth? (see p. 52, Chap. 2.)

Ans. $3.3 \times 10^{-2}$ rad.

6. *Age of the universe.* Assuming the radius of the universe given on page 4, find the age of the universe from the assumption that a star now on the radius has been traveling outward from the center since the beginning at 0.6c = $1.8 \times 10^{10}$ cm/s ($c$ = speed of light in free space).

Ans. $\approx 2 \times 10^{10}$ yr.

7. *Angles in a spherical triangle.* Find the sum of the angles in the spherical triangle shown in Fig. 1.5, assuming A is at the pole and a = radius of sphere. In order to find the angle at A, consider what would be the value of a in order for the angle to be 90°.

FURTHER READING

These first two references are contemporary texts for the high school level. They are excellent for review and clarification of concepts. The second reference contains much material on history and philosophy.


Ann Roe, "The Making of a Scientist," Dodd, Mead & Company, New York, 1953; Apollo reprint, 1961. This is an excellent sociological study of a group of leading American scientists of the late 1940s. There have probably been some significant changes in the scientific population since the book was first published in 1953.


A. Einstein, autobiographical notes in "Albert Einstein: Philosopher-Scientist," P. A. Schilpp (ed.), Library of Living Philosophers, Evanston, 1949. An excellent short autobiography. It is a pity that there are so few really great biographies of outstanding scientists, such as that of Freud by Ernest Jones. There is little else comparable in depth and in honesty to the great literary biographies, such as "James Joyce," by Richard Ellman. The autobiography of Charles Darwin is a remarkable exception. Writers about scientists appear to be overly intimidated by Einstein’s sentence: "For the essential of a man like myself lies precisely in what he thinks and how he thinks, not in what he does or suffers."


Experimental Tools of Physics. The photographs on this and the following pages show some of the instruments and machines that are contributing actively to the advancement of the physical sciences.

A nuclear magnetic resonance laboratory for chemical structure studies (ASUC Photography)
Study of nuclear magnetic resonance spectra a sample is shown spinning rapidly between the polepieces of an electromagnet to average out magnetic field variations (Esso Research).

Operator in a nuclear magnetic resonance laboratory ready to place a sample in the probe in the variable temperature controller in which the sample is spun (Esso Research).
A magnet constructed of superconducting wire, for operation at low temperature. The coils shown are rated to produce a magnetic field of 54,000 gauss. Such apparatus is the heart of a modern low-temperature laboratory. (Varian Associates)

The large radio telescope in Australia. The dish is 210 ft in diameter. It stands in a quiet valley 200 mi west of Sydney, New South Wales. In this remote location, there is a minimum of electrical interference. (Australian News and Information Bureau)
A high-energy particle accelerator: the Bevatron at Berkeley. Protons are injected at the lower right (Lawrence Berkeley Laboratory). By this time much-higher-energy accelerators are operating at the Brookhaven Laboratory on Long Island, at the CERN Laboratory in Geneva, at Serpukhov in Russia, and at NAL near Chicago.
The 200-in Hale telescope pointing to zenith, seen from the south (Photograph courtesy of the Hale Observatories)

Reflecting surface of 200-in mirror of Hale telescope and observer shown in prime-focus cage (Photograph courtesy of the Hale Observatories)
Observer in prime-focus cage changing film in the 200-in Hale telescope (Photograph courtesy of the Hale Observatories)

NGC 4594 Spiral galaxy in Virgo, seen edge on. 200-in photograph (Photograph courtesy of the Hale Observatories)
Human red blood cells viewed by the scanning-electron microscope and magnified 15,000 times. Disklike objects are the red blood cells connected by a mesh-work of fibrin strands. Note the realistic three-dimensional character of the picture. (Photograph courtesy of Dr. Thomas L. Hayes, Donner Laboratory, Lawrence Berkeley Laboratory, University of California, Berkeley)

Scanning-electron-microscope installation showing electron optical column that forms probing electron beam (left) and display console containing synchronous cathode-ray-tube beam (right). Auxiliary equipment includes piezoelectric micromanipulator in column of instrument, TV frame rate display and TV tape recorder, Polaroid recording camera, and signal monitor oscilloscope. (Photograph courtesy of Dr. Thomas L. Hayes, Donner Laboratory, Lawrence Berkeley Laboratory, University of California, Berkeley)
A 43-mi-wide Martian crater (top) was photographed by Mariner 9 on December 16, 1971. The sun shines from the right. The white dotted rectangle inscribes the area shown in the bottom picture taken by Mariner's high-resolution camera on December 22. The ridges, similar to lunar mare ridges, are inferred to be breaks in the crust along which extrusion of lava has taken place. Both pictures have been enhanced by computer processing. (Photograph courtesy of the Jet Propulsion Laboratory, California Institute of Technology, NASA)
This mosaic of two photographs of the Tithonius Lacus region on Mars taken by the Mariner 9 spacecraft revealed a canyon twice as deep as the Grand Canyon in Arizona when the pictures were compared with pressure measurements taken by the ultraviolet spectrometer experiment aboard the spacecraft. The arrows connect the depths deduced from the pressure measurements taken by the ultraviolet spectrometer and the corresponding features on the photograph. The dotted line is the scan path of the spectrometer. The photographs were taken from an altitude of 1070 mi and cover an area of 400 mi across. (Photograph courtesy of the Jet Propulsion Laboratory, California Institute of Technology, NASA)
CONTENTS

LANGUAGE AND CONCEPTS: VECTORS
Vector Notation
Equality of Vectors
VECTOR ADDITION
PRODUCTS OF VECTORS
Scalar Product
Vector Product
VECTOR DERIVATIVES
Velocity
Acceleration
Example: Circular Motion

INVARIANTS
Examples of Various Elementary Vector Operations
Problems
Mathematical Notes:
  Time Derivatives, Velocity, and Acceleration
  Angles
  The Function e^x
  Expansion in Series
  Vectors and Spherical Polar Coordinates
  Formulas for Analytic Geometry
  Useful Vector Identities

Further Reading